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COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE-   Lunar Coordinate Systems

TM- 67-1012-10

DATE- August 17, 1967

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AUTHOR(S)- D. D. Lloyd

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ABSTRACT

The distinction between a coordinate system used for spacecraft position and a coordinate system used for lunar surface feature position is shown. These two types of systems and their relative uncertainties are discussed. An analysis is presented of the problems in determining the uncertainties in position of lunar surface features relative to the Manned Spaceflight Net (MSN) estimate of spacecraft position.

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SUBJECT: Lunar Coordinate Systems
Case 340

DATE: August 17, 1967

FROM: D. D. Lloyd

TM-67-1012-10

TECHNICAL MEMORANDUM

INTRODUCTION

When a spacecraft, the CSM, the LM, or the Lunar Orbiter, is orbiting around the moon, it is tracked by the Manned Spaceflight Net (MSN) or the Deep Space Net (DSN) tracking stations and its velocity is measured relative to the earth. The tracking data is derived from MSN or DSN stations whose position is tied to the NASA geodetic net. The spatial orientation of the tracking data is obtained initially in the geocentric inertial reference frame. The tracking data is processed; during the processing it is fitted to a center of mass of the moon, as derived ad hoc from this data. The position of the vehicle is thus expressed in a lunar centered inertial coordinate system.

If, however, the moon's surface is examined by a telescope, the positions of points on the moon's surface are defined by other means. The optical data is fitted to some apparent center of the moon and mean sub-earth point* derived from that optical data. Normally the data is expressed in a lunar fixed coordinate system which is related to the iner- tial system by lunar ephemeris data which has historically been obtained by telescopic data. All cartographic coordinate systems prior to the receipt of Lunar Orbiter photographs were based solely upon earth-based telescopic data.

The differences between the two systems are important because surface feature locations are recorded in a cartographic system while the Apollo program uses tracking data as its prime source of spacecraft navigation data. Therefore, it is important to understand that these two systems are based upon distinct techniques and distinct sets of data.

These two systems and their uncertainties are dis- cussed. The uncertainty in position of lunar surface features relative to MSN position determination is of interest as one possible Apollo guidance software input.

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*Sometimes called mean libration point.

This memorandum emphasizes the distinction between these systems rather than the internal precision of either. Furthermore, it emphasizes the point of view of the Apollo navigator rather than the geophysicist.

TECHNICAL DISCUSSION

The Thin Shelled Moon

It is a useful concept to consider the moon as a thin surface shell with a separate core inside the shell and rigidly attached to the shell.

In the concept the shell is infinitely thin, infinitely strong, and of no mass. The shell has a complex shape; that of the true lunar surface. It is not quite spherical and carries the mare, the highlands, and the craters (Figure 1). The position of the shell in space is defined in relation to the center of the moon. The axis of rotation of the moon (and thus the moon's equator) and the mean sub-earth point are used to define its coordinates. Only visual data can be processed in defining the position of any surface feature.

The core, rigidly attached to the shell, generates by its complex mass distribution the gravity field of the moon (Figure 2) usually described by a series of terms defining the lunar gravitational potential.

Orbiting vehicles, such as the Lunar Orbiter and the Apollo CSM follow free fall paths determined solely by the gravity field and completely independent of the shell. The LM must, however, land on the shell, and it is the shell that is photographed by the Lunar Orbiter and by earth-based telescopes.

In order to describe positions on and near the moon, man has imposed a coordinate grid system (Figure 3). The primary definition of this coordinate system is precise; unfortunately, our ability to determine the position of a lunar feature or a spacecraft in this system is limited. In applying two nearly independent techniques (telescopic photography and radar tracking), two secondary coordinate systems have been generated which are based on distinct sets of data.

Our first opportunity to compare measurements in these coordinate systems has come with unmanned vehicles including the Ranger and the Lunar Orbiter. Our most critical requirement to remove differences between the systems (at one time and in one place) will come with the first Apollo landing.

Because much of our historical literature concerning gravitation potential has discussed the earth, not the moon, it is necessary to recognize the different conditions of the moon and the unsuitability of referring to it as if its surface could be assumed to represent the shape of the gravitation potential. Unlike the earth, there is no liquid providing an equi-potential surface that dominates the moon's surface. This does not necessarily mean that some relationship between the surface and the gravitation potential does not exist. The near spherical shape of the mare may represent an adjustment of the mare material to the lunar gravitational potential (Figure 4), whether they do or not is of interest for geophysical inference. Such analysis need not precede early Apollo landings, but an understanding of landing site position must precede the landings.

Preflight Surface Data for Apollo Navigation

It is clear that there are at present at least two sources of data on lunar surface feature position: earth based telescopes as presented in ACIC 1:500,000 charts and Lunar Orbiter photographs whose position is determined by DSN tracking data.

It is also clear that there is a need to have just one statement of preflight lunar surface landing site position data (and associated position uncertainty). (Note here that we are assuming a selected Apollo navigational mode, e.g., MSN; it is conceivable that a second different statement of position could be prepared for a second independent mode).

Therefore, starting with at least two sets of data it is necessary to either:

(1) Combine the two sets of data by appropriate processing techniques; or

(2) Reject all but one set of data (e.g., just use DSN - Lunar Orbiter data).

Either of these requires an understanding of the data sources and their uncertainties.

In-Flight Data for Apollo Navigation

Initial determinations of the CSM position will be by MSN tracking in the primary mode. This will yield a state vector determination and trajectory prediction to some epoch in a pure MSN system. The preflight landing site coordinates will be used to determine the LM descent guidance aim point.

The possible errors in preflight estimates of the latitude, longitude, and altitude of the landing site relative to the MSN coordinate system will influence the uncertainty in LM aim capability. A growing awareness of this effect has resulted in a recent decision* to sight on a sighting mark near the landing site using the CSM guidance optics while in the primary guidance mode. If the sighting data is suitably processed, it can be used in real time to relate the CSM trajectory to the landing site (Figure 5).

The study which determines the method of combining the sighting data with preflight and MSN data must consider the estimated relative uncertainties in the MSN data, preflight landing site data, and the real time on board optical sighting data.

The back-up navigation system, using several lunar sighting marks, introduces additional coordinate uncertainty problems.

Uncertainties Between Coordinate Systems

Until recently, the method of deriving lunar feature position data had to use earth-based stereoscopic photography. Several map control grids have been derived from such data by ACIC and AMS. A discussion of the geometric relationship between the ACIC control grid and the AMS control grid is provided in Reference 1.

The accuracy of the earth based telescopic system is limited by viewing through the earth atmosphere and by the poor (small angle) stereoscopic conditions, which are based solely on lunar librations. Kopal in Reference 2 suggests that the viewing limit is .25 sec of arc or 506 meters on the lunar surface. He estimates that, "The deficiencies inherent in the present system of selenographic coordinates...are probably displacing whole lunar regions by several kilometers relative to others;..."[2]

Uncertainties of position of a landing site must include the uncertainties in preflight selenographic coordinates if these are used to define the position of the landing site.

Independent use of the MSN to relate the LM to such a landing site would, therefore, introduce uncertainties of several kilometers in LM aim CEP if Kopal's comments are confirmed.

A preliminary evaluation of various sources of data implies that uncertainties of several kilometers exist.

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*ASSB meeting on March 29, 1967

Ranger Position Uncertainties

The Ranger spacecraft missions VI, VII, VIII, and IX provide further indications of uncertainties between the tracking net coordinate system and the selenographic coordinate system based on earth-based telescopic data. All four provide data pertinent to radial measurements: Rangers VII, VIII and IX provide data pertinent to tangential position uncertainties.

Radial Uncertainties

Rangers VI through IX impacted later than expected by about 1 (one) second (References 3 & 4). At an impact velocity of 2 km/second radially (the spacecraft did not impact radially but we are concerned here with the velocity vector in the radial direction) this corresponds to a radial error of 2 km.

It is necessary to check that this was not simply due to the spacecraft hitting a deep depression. This is confirmed by the photographs of the last 3 Rangers and by an examination of the apparent elevation distances in the Ranger VI impact area.

It is clear then that an uncertainty exists of about 1 sec or 2 km radially. It may be that this is due to some bias in the DSN tracking net. However, the removal of such a bias simply by subtraction leaves undetermined whether such a radial error will exist for later missions, particularly those based on a different net, i.e., the MSN.

Tangential Uncertainties

The ACIC maps made from Ranger VII, VIII and IX data determine the impact point solely from photographs of the lunar surface. The intersection of the camera center tracks provide a selenographic data point based directly on the lunar surface features.

When these points are measured in the ACIC selenographic coordinate system, the following coordinates are obtained.

Ranger VII	20° 35'18" W	10° 37'50" S from (RLC-4)
Ranger VIII	24° 42'00" E	2° 39'00" N from (RLC-6)
Ranger IX	2° 22'14"W	12° 49'56" S from (RLC-17)

When these same impact points are measured in the selenocentric coordinate system based on DSIF radar data, the following coordinates are obtained:

Ranger VII	20° 40' 48" W	10° 40' 48" S	Ref. 3
Ranger VIII	24° 48' 36" E	2° 42' 36" N	Ref. 4
Ranger IX	2° 22' 48" W	12° 54' 36" S	Ref. 4

Giving the following tangential errors:

Ranger VII	0° 05' 30" (2.5 km) E-W, 0° 03' 02" (1.5 km) N-S
Ranger VIII	0° 06' 36" (5.5 km) E-W, 0° 03' 36" (3 km) N-S
Ranger IX	0° 00' 34" (.3 km) E-W, 0° 05' 40" (3 km) N-S

It is possible to adjust the radial error such that the minimum tangential error results. However, the tangential improvement is not great and it is unreasonable to allow the radial adjustment to be independent from one mission to the next.

The tangential errors between coordinates are therefore indicated to be of the order of a few kilometers.

Another independent check on uncertainties

The Russians have published a map of lunar surface features in the vicinity of the Luna IX landing, showing the touchdown point at 64° 22' W and 7° 8' N, based on their latitude/longitude grid*. When the features are matched to the corresponding ACIC chart, the coordinates of the landing point are 64° 32' W, 6° 58' N, in ACIC coordinates. An error of 10' or 5 km both north-south and east-west exists.

[Note: The relationship to tracking is not involved here. The position of Luna IX is only incidental to the discussion here.]

Such a difference is another measure of the uncertainties inherent in any selenographic coordinate system based on telescopic control.

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*PRAVDA, February, 1966

USE OF LUNAR ORBITER PHOTOGRAPHY

A preliminary analysis of Lunar Orbiter II photography indicates that Apollo candidate landing sites may have positional uncertainties of the order of 3 km when compared to ACIC 1:500,000 maps (Reference 10). This adds substantiation to an estimate of uncertainties of a few kilometers in maps derived from earth based telescopic data. However a direct use of the Lunar Orbiter to define lunar surface features may produce less uncertainties relative to the MSN.

The orbit of a Lunar Orbiter has one of its foci at the center of mass of the moon. Its orbit is solely dependent upon the gravitational field. The orbit of the Lunar Orbiter is determined by the earth-based radar tracking. Orbit determination is achieved by fitting the radar doppler range rate data to an elliptic orbit that has as its focus the apparent center of mass of the moon. (The program that processes the data can accommodate perturbation terms.) The Lunar Orbiter takes pictures of the surface and from data contained in the photographs the lunar surface can be related to the position of the spacecraft at the time of photography. The position of the spacecraft at the time is obtainable from tracking data on the Lunar Orbiter.

By this method the landing site and any navigational sighting marks can be positioned relative to the apparent center of the moon and thus to the DSN selenocentric coordinate system, tied to the NASA geodetic net.

The CSM's position when it reaches lunar orbit is tracked by earth-based radars tied to this same NASA geodetic net, but primarly through MSN stations. Positional uncertainties involved in each orbit determination procedure may exist (Ref. 7, 8 & 9), but these may not need to be added because appreciable correlation will exist. It is possible that this correlation would reduce the uncertainty due to biases and noise to a few hundred meters.

Consider the hypothetical case where the Lunar Orbiter has no uncertainties in surface position determination other than those due to uncertainties in DSN tracking. Then in determining position of a surface feature relative to MSN for Apollo, one need only consider uncertainties between the nets. Since MSN and DSN simultaneously track the Lunar Orbiter at certain times, the uncorrelated biases can be removed for those epochs.

However, certain uncertainties do remain. The relationship between the position of the Lunar Orbiter and the landing site in its photographs includes uncertainties of a few hundred rather than a few thousand meters. This, together with the time-dependence and correlated uncertainties between the MSN and DSN position determination may produce a total relative uncertainty of the order of 1 km.

CONCLUSIONS AND RECOMMENDATIONS

Several coordinate systems are involved in Apollo navigation to a lunar surface feature defined landing site. Some of the uncertainties involved are significant.

The relative uncertainty of lunar surface features relative to MSN position determination is difficult to determine, yet is needed by Apollo navigation. This situation requires that continuous effort be maintained toward the goal of reaching at least an understanding of the nature of problems and an estimation of the magnitude of the uncertainties. These estimates will influence Apollo navigation and guidance by determining the types of location data used and their relative weighting factors.

At the present time, it appears that the method of defining the co-ordinates of Apollo landing sites should depend heavily on data from Lunar Orbiter and the DSN net.

D. D. Lloyd

1012-DDL

Attachments:
  References
  Figures 1-5

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8. R. H. Tolson and H. R. Compton, Accuracy of Determining the State of a Lunar Satellite and the Lunar Gravitational Field, Journal of Spacecraft and Rockets, January, 1967.

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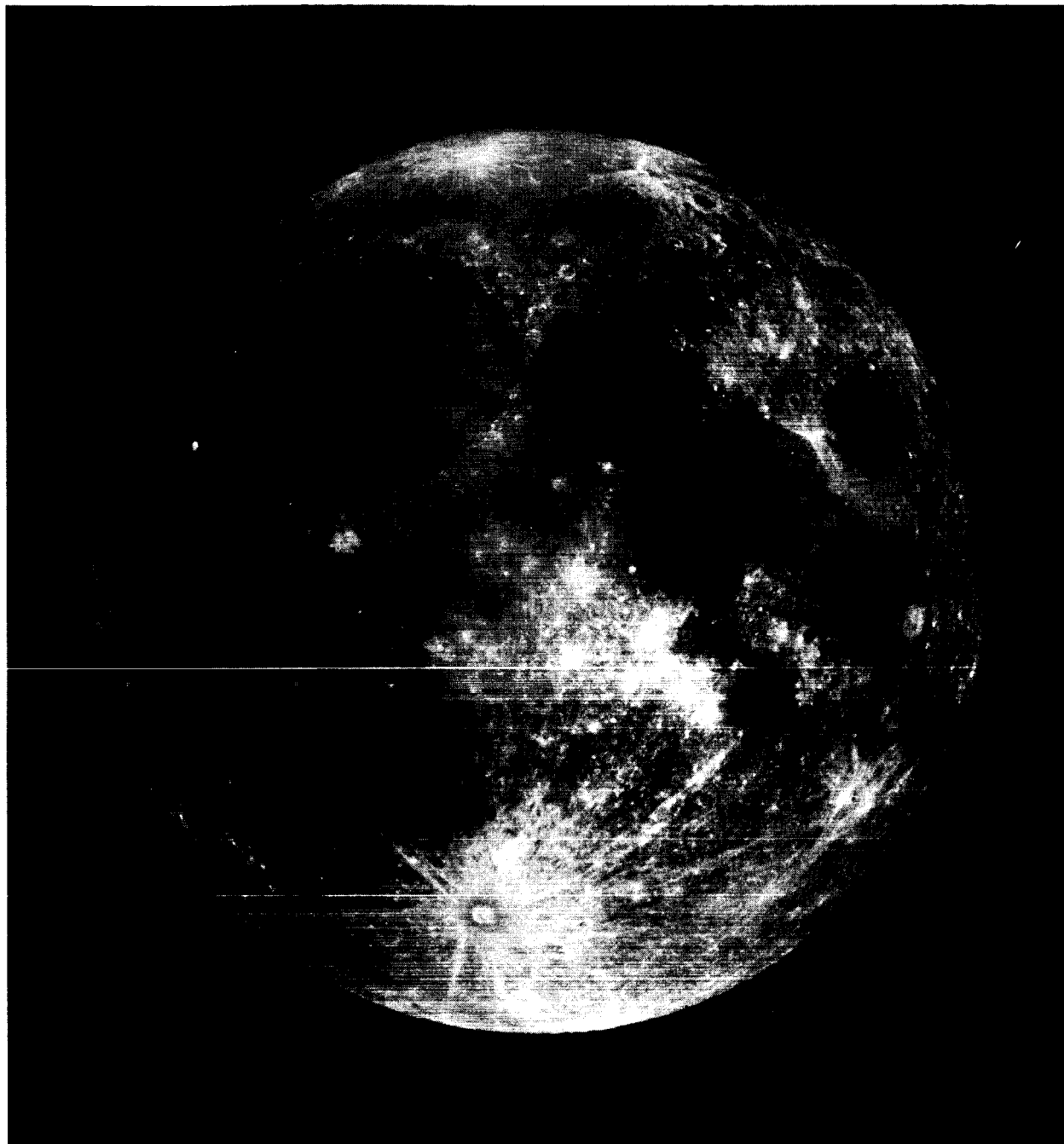
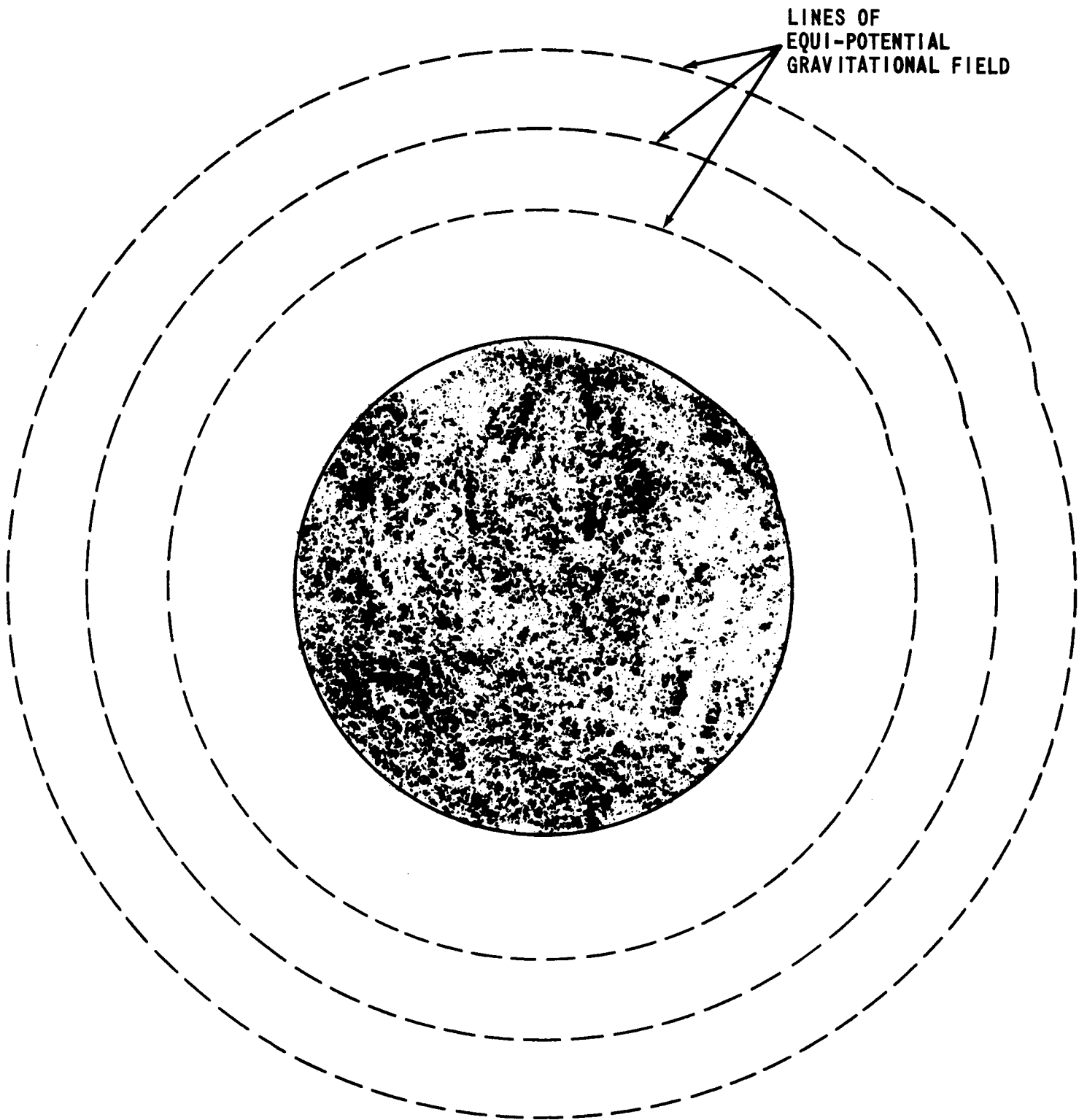FIGURE 1   ACTUAL SURFACE-OUTER SHELL

LINES OF
EQUI-POTENTIAL
GRAVITATIONAL FIELD

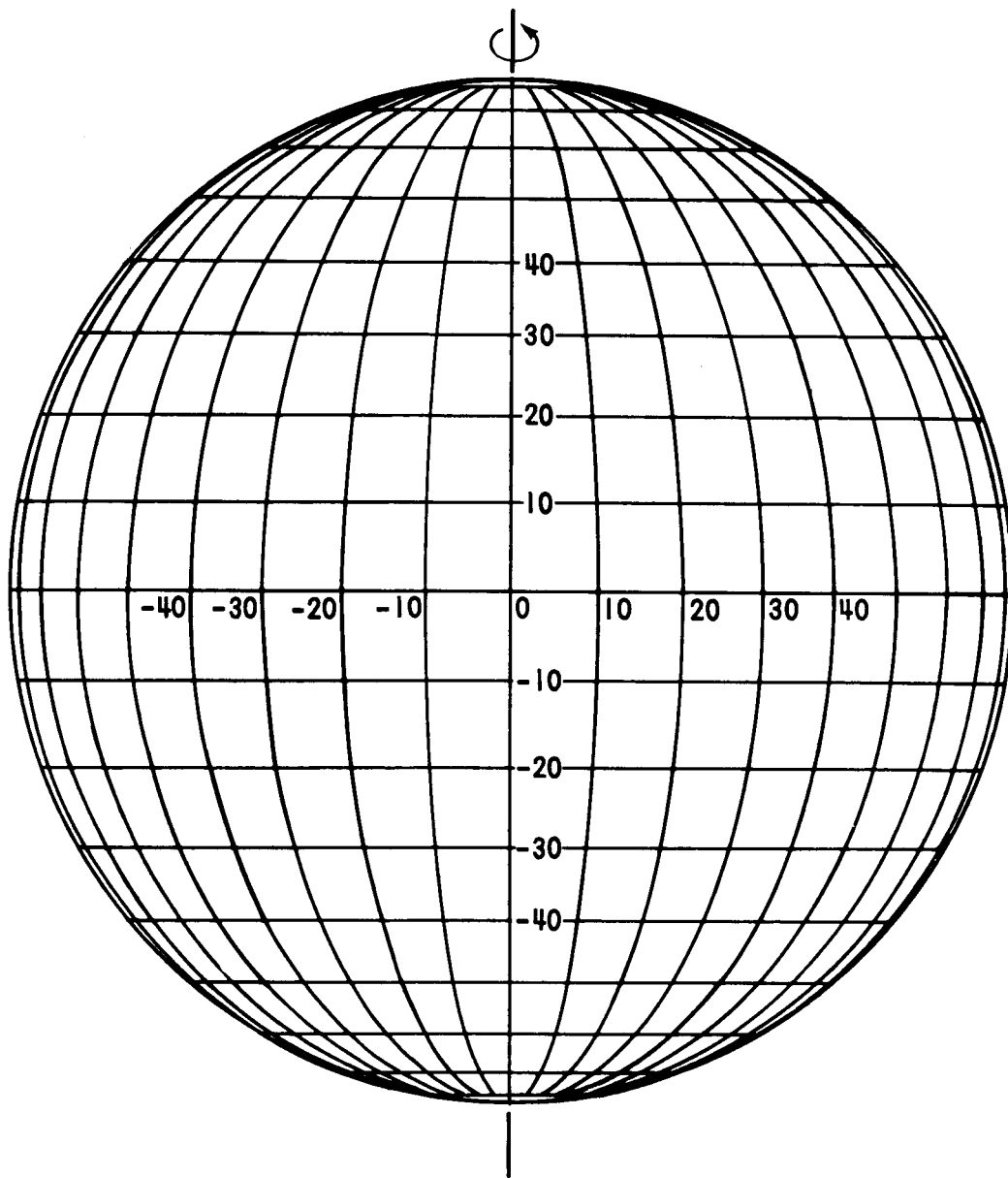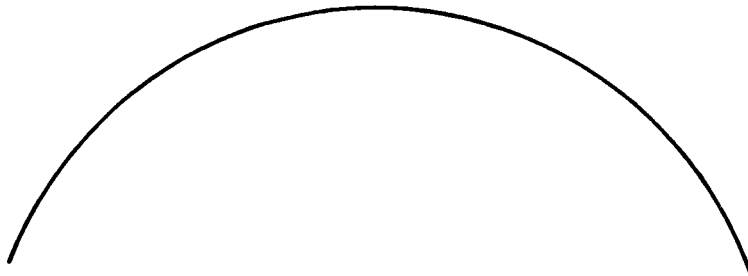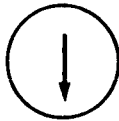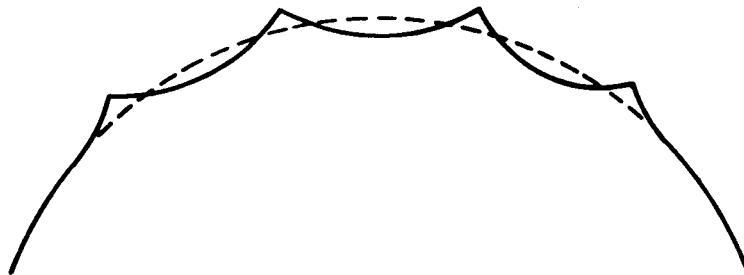FIGURE 2   ACTUAL MASS REPRESENTED AS INNER CORE

FIGURE 3   MAN MADE COORDINATE GRID

PRIOR TO IMPACT

POST IMPACT - EARLY

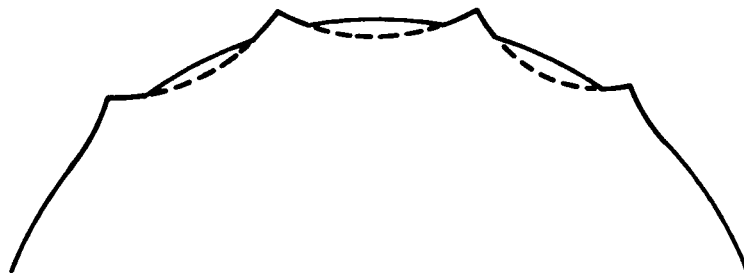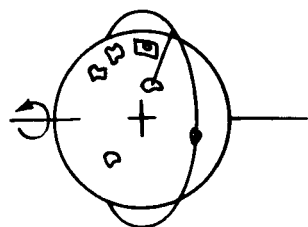**POST IMPACT - ADJUSTED BY GRAVITATION POTENTIAL**
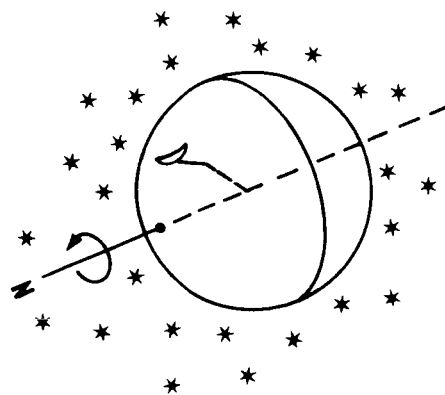
FIGURE 4   MARE ADJUSTMENT TOWARDS EQUAL POTENTIAL SURFACE

INERTIAL

GEO-INERTIAL (NASA GEODETIC TRACKING NET)

FIGURE 5   A SELENOCENTRIC COORDINATE SYSTEM BASED ON NASA GEODETIC TRACKING
LANDING SITE ZERO SET TO CSM